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HALL EFFECT DEVICES AS MAGNETOMETERS IN CRYOGENIC APPLICATIONS

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IN CRYOGENIC APPLICATIONS

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SUMMARY

Eight representative samples of commercial Hall effect devices were tested at 4.2° K to determine their utility as magnetometers for cryogenic applications. Although cool-down periods of 10 to 15 minutes were used in an attempt to reduce the thermal shock, several units failed after one or more immersions in liquid helium. The low-temperature behavior of the tested units differed qualitatively from the room temperature response in that there were oscillations in the Hall voltage as a function of magnetic field. The procedure for use and the low-temperature response of the devices to magnetic fields up to 70 kilogauss are discussed.

INTRODUCTION

Investigations of superconductivity and the magnetic behavior of materials at very low temperatures often require a measurement of magnetic fields in small volumes. Among the many techniques that are used to measure magnetic fields (ref. 1) are the magnetoresistance of bismuth wire, the saturation of ferromagnetic materials, nuclear magnetic resonance, the use of search and rotating coils, and the Hall effect.

Probably the most widely used magnetometer for low-temperature application takes advantage of the large magnetoresistance of bismuth. The resistance of the bismuth wire at a given temperature is directly related to the magnetic field present, but this resistance occasionally changes unpredictably.

Flux gate techniques, which utilize the abrupt saturation of certain ferromagnetic materials, have yet to be applied to low-temperature work. This method should be applicable at cryogenic temperatures but not in magnetic fields of the order of 50 to 100 kilogauss because of the relatively low saturation levels of ferromagnetic materials.

Nuclear magnetic resonance methods determine magnetic fields through a measurement of the frequency of precession of nuclei in a magnetic field. For proper operation, this technique needs highly homogeneous fields, but this condition is not often satisfied in practice.

The use of a rotating coil is mechanically troublesome at low temperatures, since moving parts tend to frost and jam.

One technique that has been used successfully at low temperatures is the use of a search coil. This technique involves the time integral of the output of a coil as it is brought into or removed from the test area or as the field is established with the coil in place. This method yields a measure of the magnetic flux through the coil and hence the magnetic field there. Adaptation of this technique for continuous measurement is difficult.

The Hall effect seemed to offer the most promise for high field measurement at low temperatures, and it was therefore decided to investigate commercially produced Hall effect probes. Although Hall effect devices have been studied for many years, their use as magnetometers for cryogenic applications has been neglected. In the present study eight commercial Hall devices were tested in magnetic fields up to 70 kilogauss at liquid-helium temperature (4.2° K).

HALL EFFECT

A charge moving in the presence of a magnetic field experiences a Lorentz force given by $q\vec{v} \times \vec{B}$, where q is the charge, $\vec{v}$ is its velocity, and $\vec{B}$ is the field strength. When charge carriers are constrained to move in a conductor, the carriers tend to be deflected toward one of the boundaries of the conductor. These deflected carriers establish an electric field E_H, which cancels the Lorentz force. The Hall voltage V_H, which is this electric field times the width of the sample w, can be used as a measure of B. For the free-electron model of metals the relation is given by

$$V_H = E_H w = vBw = R \frac{IB}{t}$$

where $R = 1/ne$ is called the Hall coefficient, I is the control current, t is the sample thickness, n is the number of conduction electrons per unit volume, and e is the electronic charge. For conductors, v is small because of the large concentration of conduction electrons, whereas in semiconductors the charge carrier velocity is quite large. Substances such as indium arsenide and indium antimonide (ref. 2) exhibit large carrier velocities and hence produce usable Hall voltages. For these particular semiconductor materials the Hall voltage is known to have only a small temperature dependence, at least near room temperature. The above simplified Hall voltage relations are not strictly valid for semiconductors. The relation $V_H = RIB/t$ can be retained, but R is a more complicated coefficient than $1/ne$.

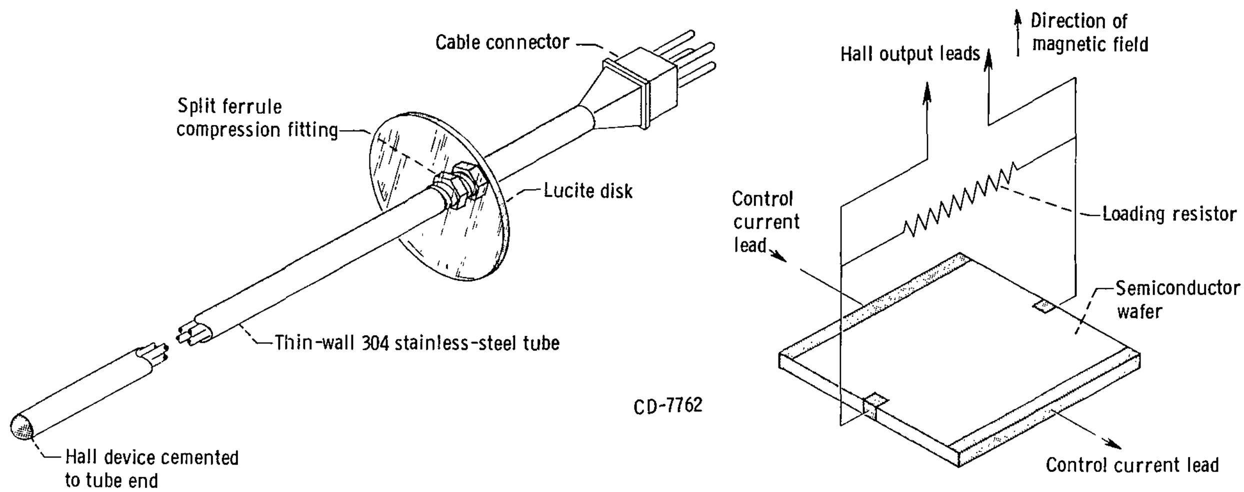
APPARATUS AND PROCEDURE

Hall Effect Devices

Tests were performed on representative devices produced by several manufacturers. These samples were of both transverse and axial designs and of many different sizes. The actual sensing area or active area ranged from about 0.03 to about 0.0036 square inch. Even smaller units of both the axial and the transverse types are available.

Experimental Details

Each device was attached with an epoxy cement to one end of a type 304 stainless-steel thin-wall tube with the lead wires contained within the tube. A plastic disk was attached to the top of each tube by a compression fitting with split ferrule to allow probe length adjustment. This disk supported the probe in a stainless-steel Dewar and established the correct position of the probe in the center of a high-field solenoid. The solenoid used was water cooled with a 4-inch inside diameter. Its construction and performance are described in reference 3. The probe and the Hall device are illustrated in figure 1.



(a) Probe construction.

(b) Hall effect device.

Figure 1. - Construction of probe and typical Hall effect device.

The measured variation of resistance with magnetic field for a typical Hall effect device at 4.2° K is shown in figure 2. With large magnetoresistance effects it is important to have a constant-current power supply with adequate range to produce the d-c control current for the device.

The Hall output voltage as a function of the magnetic field was recorded by an xy plotter. The proportionality of the solenoid current to the field produced by the solenoid allowed the x-axis to be calibrated directly in kilogauss.

Tests were performed at room temperature and at liquid-helium temperatures. In these tests the current to the device was held constant to within 0.1 percent, and the magnetic field was varied. The room-temperature measurements were performed first to establish a basis with which to compare the low-temperature behavior of the device.

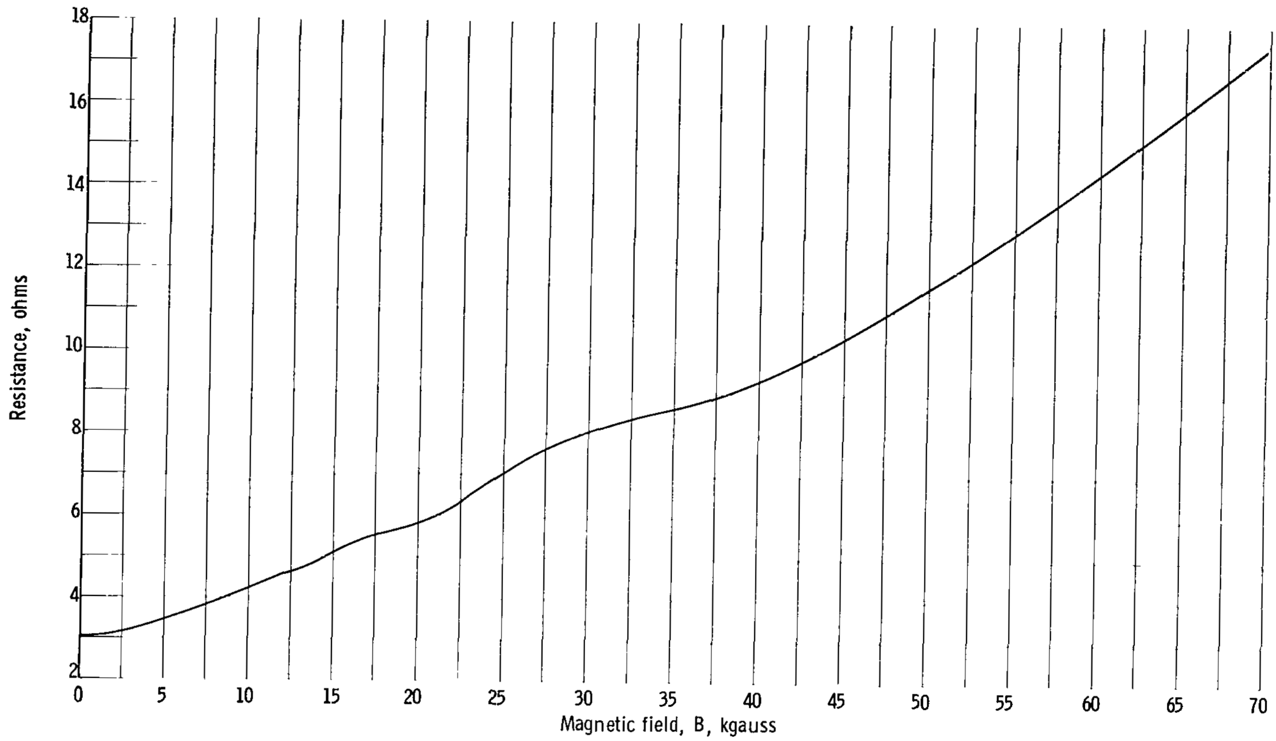


Figure 2. - Effect of magnetic field on input resistance of Hall device at 4.2° K.

RESULTS AND DISCUSSION

Room-Temperature Tests

Near room temperature (277° K), most of the devices showed a nearly linear response to magnetic field up to 70 kilogauss, as illustrated in figure 3. Since the operation of all of the devices tested under these conditions was similar, only a typical curve is shown.

Liquid-Helium-Temperature Tests

The procedure that was adopted for cooling the units to liquid-helium temperature (4.2° K) required 10 to 15 minutes for completion and consisted of slowly lowering the probes into liquid nitrogen, then into the cold helium gas, and finally into the liquid helium itself. Unfortunately, not all of the probes withstood the thermal shock. One unit of the original eight failed on the first test. Other units failed in later tests, and the general nature of these failures indicated that they were due to separation of the electrical connections in the sensing elements as a result of differential expansions and contractions of the probe materials. This fault could probably be corrected by appropriate redesign of the sensing element.

The control current used was 10 milliamperes, even though some of the units were rated for a current up to 500 milliamperes at room temperature.

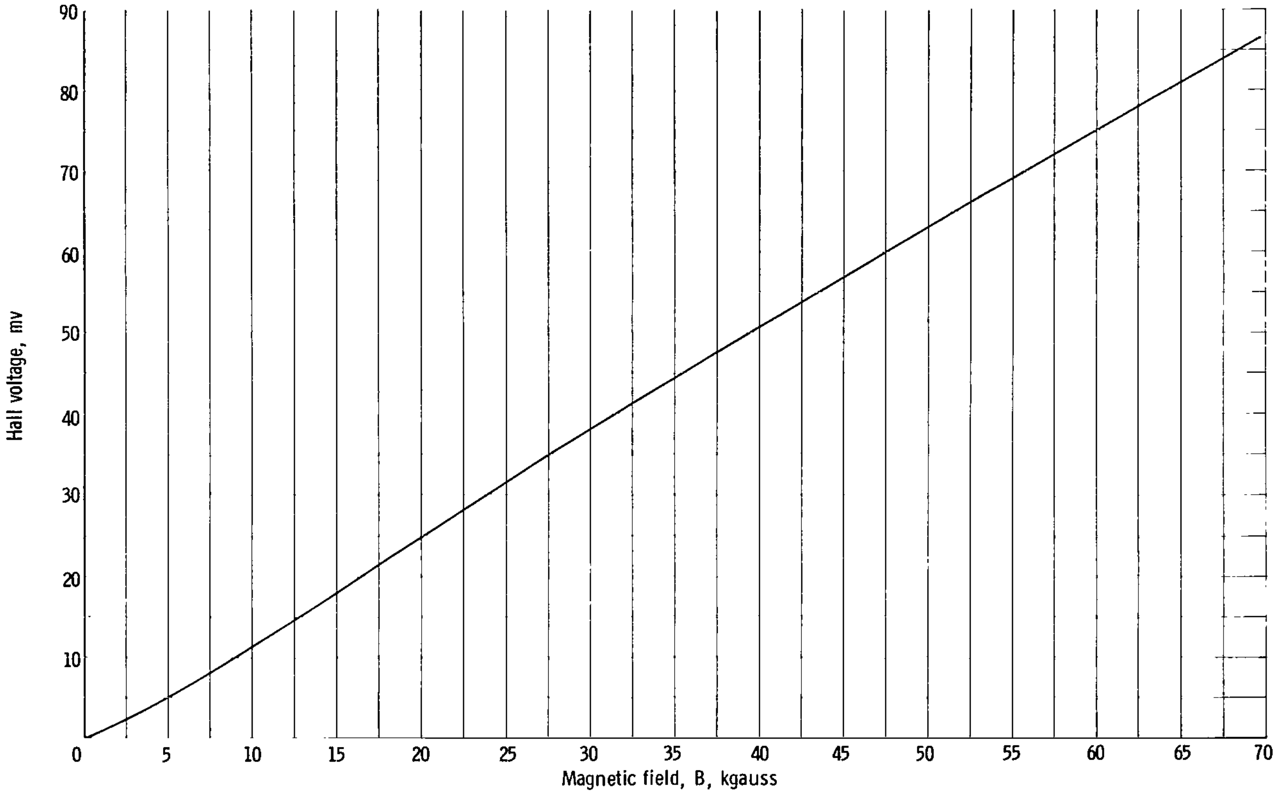


Figure 3. - Field dependence of Hall voltage at 277^0 K.

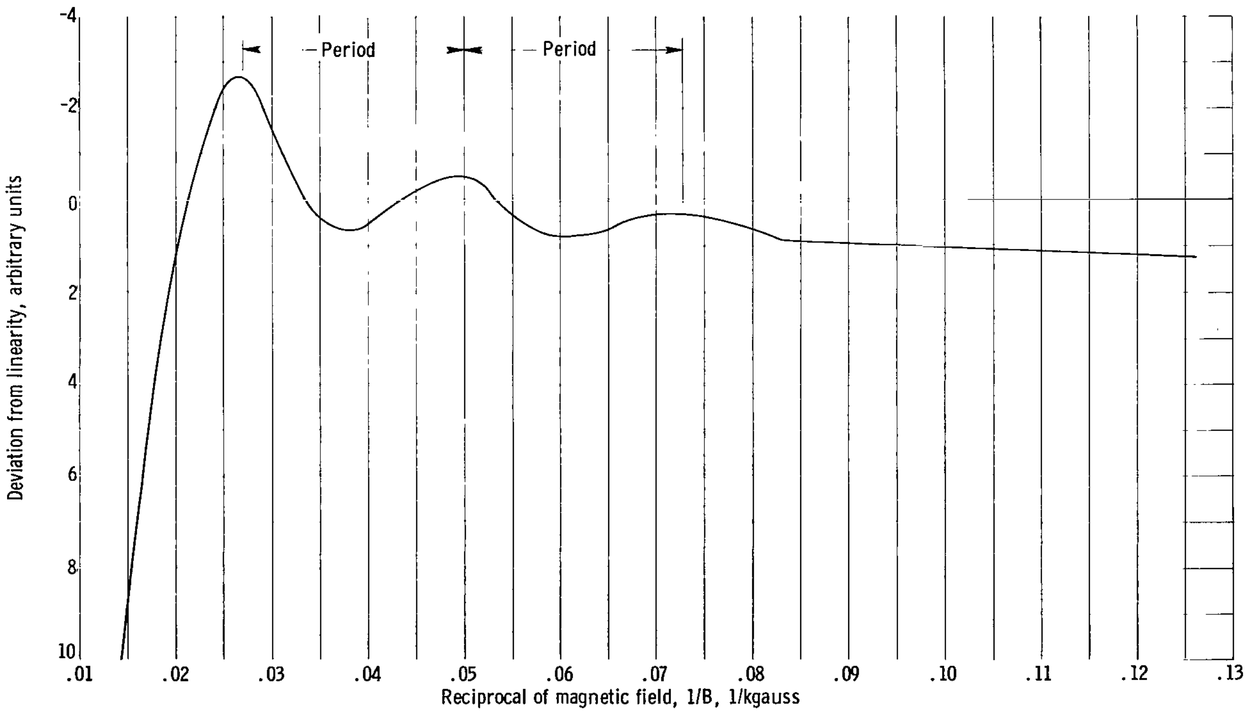


Figure 4. - Deviation from linearity of voltage output of Hall effect device at 4.2^0 K with periodic nature of oscillations shown.

Since the resistance increased so much with increasing magnetic field, the current was kept low to limit ohmic heating in the sample. Currents of about 100 milliamperes caused heating of the Hall devices. Such high currents were unnecessary, however, and wasteful of liquid helium.

At liquid-helium temperature the Hall voltage output of the devices as a function of field strength deviated more strongly from linearity than at room temperature. If the deviations of the curve from a straight line are plotted against inverse field $1/B$, they reveal a periodicity such as that shown in figure 4. The periodic nature of these oscillations probably arises from processes analogous to those producing the de Haas - van Alphen effect in the magnetic susceptibility.

At room temperature the output voltage at zero magnetic field (null voltage) was less than 50 microvolts at a control current of 10 milliamperes. This value changed drastically for some of the devices when they were immersed in liquid helium. Since this voltage arose from misalinement of the voltage contacts, it implies again that the contacts and leads were being stressed by thermal effects.

Figure 5 illustrates typical output for several units operated at 4.2° K. In general, all of the units yielded outputs that were very similar with the

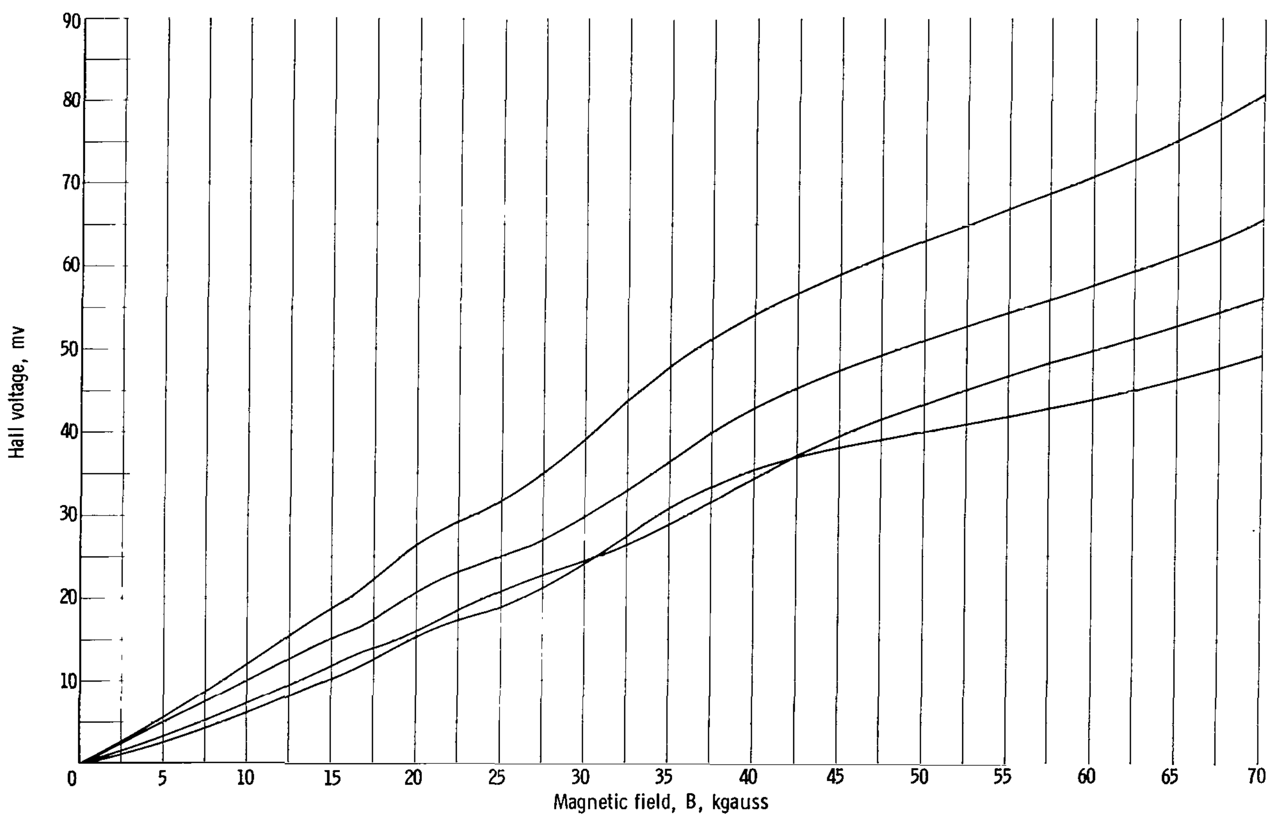


Figure 5. - Voltage characteristics of several Hall effect devices at 4.2° K as function of externally applied magnetic field.

exception of one unit, which gave considerably higher results because it was made from evaporated films laid onto a ferrite substrate.

An attempt was made to linearize the output of each device at 4.2° K in the range of 0 to 15 kilogauss. The output of certain units could be forced to have only small deviations from linearity by properly loading the Hall output with a resistance (fig. 1; see p. 3). The deviation from linearity under optimum resistive loading varied from device to device but was often less than 2 percent. A typical example of the process of linearization of the Hall voltage is shown in figure 6.

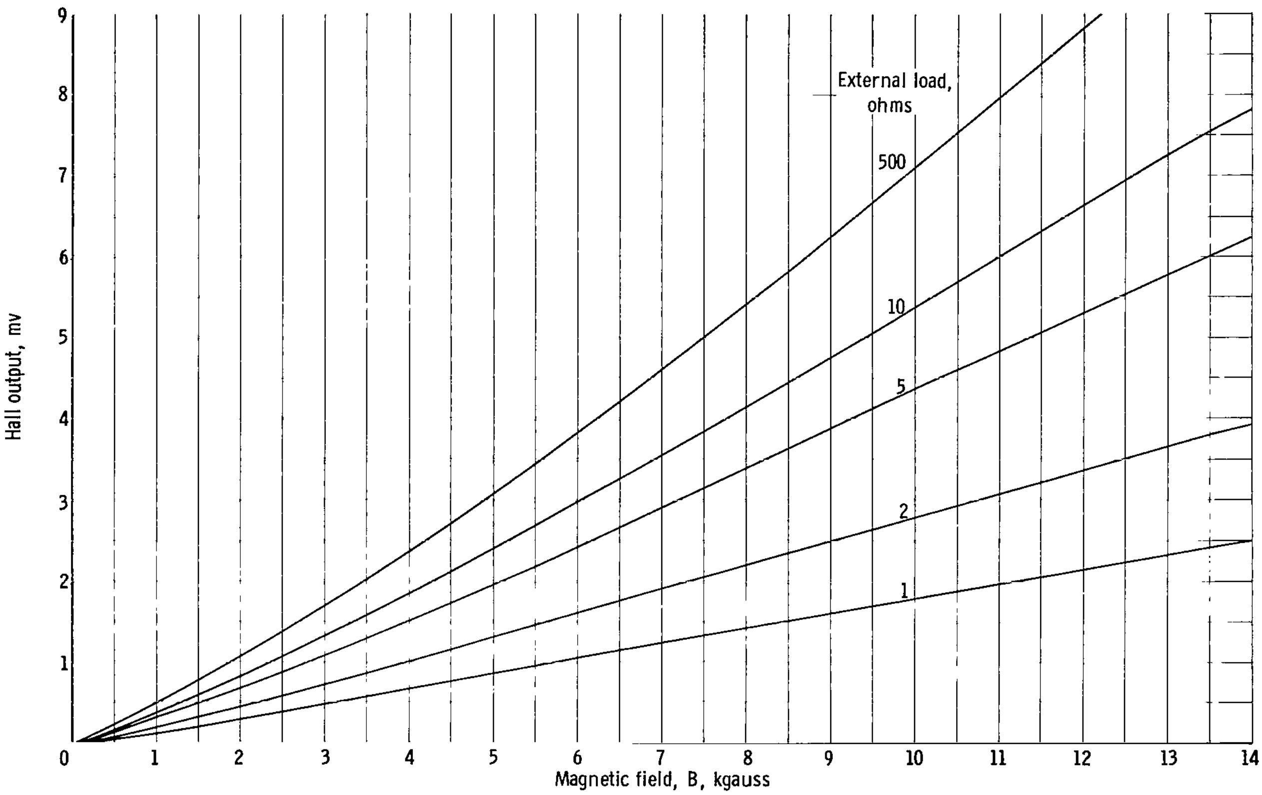


Figure 6. - Linearization of Hall output at 4.2° K with external loading.

In addition to the data taken at 4.2° K, data were also taken at 1.3° K for one unit. The data taken at these two temperatures agreed to within 1 percent. All of the devices tested were therefore expected to be similar in this respect and not to exhibit significant changes in this temperature range.

SUMMARY OF RESULTS

Eight commercially produced Hall devices were tested and found to be useful for low-temperature magnetic field measurements. The Hall voltage output at 4.2° K increased with magnetic field but contained oscillations contributed by processes analogous to those causing the de Haas - van Alphen oscillations of the magnetic susceptibility. For the one sample tested at 1.3° K the change in temperature from 4.2° K had very little effect on the Hall voltage as a function of magnetic field strength. Failure of some of the devices occurred during the cool-down process because of breakage of contacts to the semiconducting material. Designing and constructing devices that will withstand this thermal shock without damage seems feasible.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 4, 1964

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